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The History of Lake Superior Regulation: Implications for the Future

Anne H. Clites[1,*] and Frank H. Quinn[2]

[1]*Great Lakes Environmental Research Laboratory/NOAA*
2205 Commonwealth Blvd.
Ann Arbor, Michigan 48105

[2]*Scientist Emeritus*
Great Lakes Environmental Research Laboratory/NOAA

ABSTRACT. *Lake Superior outflows have been regulated for the past 80 years. The last 15 years have encompassed both extremely high water supplies and lake levels and subsequent drastic declines in the levels of Lakes Superior and the lower lakes. The IJC is considering a study whose purpose would be the reexamination of the current Lake Superior regulation plan, which has been in use since 1990. In preparation for that discussion, several different aspects of past and potential future Lake Superior levels were analyzed. The stage-discharge equation representing natural flow conditions for the pre-1900 Lake Superior outlet was used to simulate "unregulated" Lake Superior outlet conditions, using actual water supplies. Net basin supplies developed for a climate change study were used to evaluate the potential effects of regulation on future levels. A 50,000 year set of stochastic net basin supplies, based upon the present climate, was also used to provide hypothetical upper and lower bounds. By comparing recorded Lake Superior levels to what might have happened in the absence of regulation and what may occur with future supplies, it is hoped that the development and/or evaluation of any future adjustments to the regulation criteria for Lake Superior might be aided.*

INDEX WORDS: *Lake levels, lake level management, Lake Superior, regulation history.*

INTRODUCTION

Lake Superior, the largest lake in the world by surface area, drains an area of over 200,000 square kilometers, including the lake itself (Fig. 1). Lake Superior flows to Lake Huron by way of the 101-kilometer-long St. Marys River. Under natural conditions the river's outlet was controlled by the St. Marys rapids; the rock ledge at the head of the rapids acting as a submerged weir. Starting in the late 1800s, serious encroachments were made on the natural regime of the Lake Superior/St. Marys River system for power, transportation, and navigation. 1887 is generally thought of as the last year of the natural system.

Although Lake Superior is a "regulated" lake, it is important to understand that the levels and flows are only controlled to a certain extent. Regulation has allowed a moderation of the levels and flows of Lake Superior, within limits that are dictated by nature. Lake Superior, with a volume of over 12,000 cubic kilometers and retention time of 173 years, has an immense hydraulic "memory." The St. Marys River has a limited capacity to pass the water downstream. Regulatory works on both Lakes Superior and Ontario have succeeded in limiting lake level fluctuations which has encouraged more intensive shoreline development. The remainder of the Great Lakes system is naturally regulated due to the large lake surface areas and constricted outlet conditions.

Lake Superior is not only the largest managed freshwater body in the world, but also was one of the first major managed water resources in the U.S. and Canada. The legal doctrines that direct the management of this mighty resource between the U.S. and Canada are based on the Boundary Waters Treaty of 1909, which established the International Joint Commission (IJC), and the Orders of Approval of 1914. The water resources planning of that era was based on the industrialization of the U.S. and Canada with emphasis on commercial navigation and low head hydroelectric power. There was minimal consideration of concerns that today

*Corresponding author. E-mail: anne.clites@noaa.gov

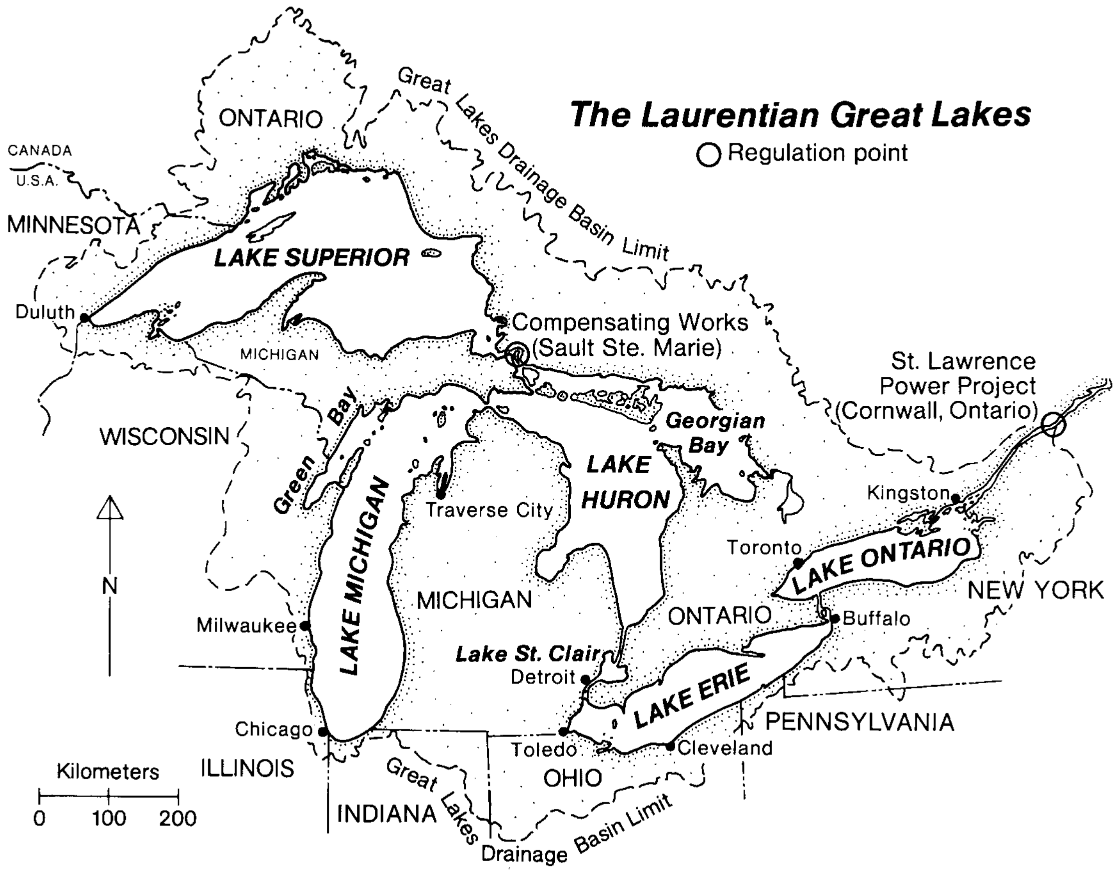

FIG. 1. Great Lakes basin map showing regulation points.

play a major role in resource planning such as ecosystem health, recreational boating, and shoreline property rights. The regulation plan currently in use for Lake Superior, Plan 1977-A, as well as those that preceded it, was based on historical water management values that may undervalue current concerns and interest groups. It may be time to reevaluate the basic tenets underlying Lake Superior regulation to ensure that all interests are represented.

The goal of this study is to trace the history of Lake Superior regulation and to recommend a series of alternative scenarios of water supplies with which to test future water management plans. The most recent modifications to the regulation plan were based only on comparisons with regulated lake levels and not with the levels that would have occurred under unregulated conditions. A number of different scenarios are described here that should be useful in evaluating the current regulation plan and what changes are needed. These include: a simulated set of levels based on the pre-regulation natural rating (1887 conditions), a set of levels representing a simulation of actual supplies under the current regulation plan, two climate change scenarios, and a scenario based upon 50,000 years of stochastically developed water supplies. The effects of regulation on water levels are explored and compared with the levels that could have existed in an unregulated state given the same water supplies. These scenarios and analyses provide an essential starting point for the upcoming Lake Superior water management analysis. This paper also attempts to draw together the important history of Lake Superior regulation, much of which is documented in unpublished government reports unavailable to many.

HISTORY OF REGULATION

During the 19th century, the St. Marys River was naturally controlled by the rocky ledge at the Lake Superior outlet. In 1888, construction of the International Railroad Bridge was completed. The piers for this large bridge were located near the head of the St. Marys rapids, reducing the discharge capacity of the river by 9% (Coordinating Committee 1994). Power diversion canals, built by both the U.S. and Canada in the 1890s, increased the flow capacity of the river to an extent that a structural flow reduction device had to be added. In 1901, the Canadian Lake Superior Power Company began to construct "compensating works" at the head of the rapids on the Canadian side. These consisted of four sluice gates, each of which was 16 meters wide between large masonry piers. U.S. and Canadian ship and power canals were added by 1914, significantly reducing the discharge cross-section of the St. Marys (IJC 1914). Regulating the sluice gates allowed control over water depth in the navigation channels and also made it possible to maximize hydropower production. Power diversions and navigation dredging only partially compensated for the reduced channel capacity of the St. Marys. These changes had raised Lake Superior's average level by 0.18 meters prior to the onset of regulation. (Coordinating Committee 1994).

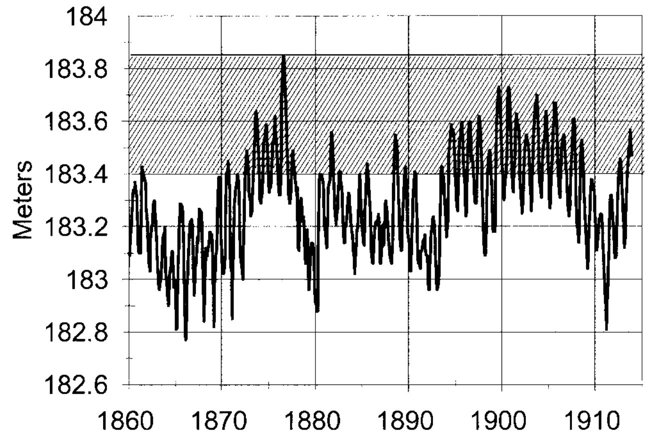

FIG. 2. 1860 to 1913 Lake Superior hydrograph. The hatched area shows regulation limits established by the 1914 Order of Approval, 183.4 and 183.86 m, IGLD 85.

The Evolution of Regulation Limits

The Boundary Waters Treaty of 1909 charged the IJC with overseeing any "use or obstruction or diversion" of international boundary waters that would affect levels or flows in both countries (IJC 1965). The treaty clearly spelled out the order of precedence the IJC was directed to follow in making decisions about the use of international waters:

"1) Uses for domestic and sanitary purposes;
"2) Uses for navigation, including the service of canals for the purposes of navigation;
"3) Uses for power and for irrigation purposes."

Since this document was written in 1909, no mention was made of flood protection, recreation, boating, or the environment. Shortly after the treaty was created, the IJC received applications from both U.S. and Canadian power companies to construct and operate additional compensating works at the head of the St. Marys River for the purpose of increasing their power diversions without adversely affecting the levels of Lake Superior. Two sets of hearings were held in the spring of 1914 to investigate the natural range of Lake Superior levels (based on 1860 to 1913) as well as to estimate the impact of the proposed actions. The decision, termed Order of Approval (IJC 1914) and as later amended, Supplementary Order of Approval (IJC 1979), set down formal guidelines for how the regulation of Lake Superior would be accomplished. The regulation limits are illustrated in Figure 2. The Order states (IJC 1914; page 4, section 5):

> "All compensating works . . . shall be so operated as to maintain the level of Lake Superior as nearly as may be between levels 602.1 and 603.6. . . . [183.4 and 183.86, meters, IGLD 85] . . . in such manner as not to interfere with navigation."

These levels refer to the datum of 1903, which translates to 600.5 and 602.0 ft, IGLD 55 when using the mean of the differences between five gages to make the datum adjustment (Hartmann 1988). Government engineers acknowledged during the hearings that the extreme range of the levels of Lake Superior based on 1860 to 1913 was 3.5 feet (1.07 meters). Although the operational goal for the range under regulation was 1.5 feet (0.46 meters), under non-average supply conditions, the range would be broadened to 2.5 feet (0.76 meters) as it was agreed by the engineers that keeping the average level in a more narrow range would not be practical.

> "The best we can do with the compensating and regulating works is to permit the lake to fluctuate over a range of about 2.5 feet, with the belief that the maximum which it will reach can be regulated to about 604 feet [184 meters, IGLD 85], and the minimum to which

> it will be allowed to fall will be about 601.5 feet [183.25 meters, IGLD 85].” (IJC 1914).

It was specified that the mean level of Lake Superior be determined by averaging at least four automatic gages, half in the U.S. and half in Canada. The 1914 Order of Approval also created the International Lake Superior Board of Control (ILSBC) as the authority to oversee this regulation. Additional gates were added on both the U.S. and Canadian sides until 1921, when full control of the outlet of Lake Superior was achieved. The 16 gate structure, nearly 305 meters long, is operated jointly by the U.S. and Canadian governments through the International Lake Superior Board of Control.

The needs of navigation dominated the discussion of allowable levels for Lake Superior during the 5 days of IJC hearings in 1914. Shipping in the Great Lakes was a $44 million industry in 1913 (IJC 1914). Although shipping and hydropower were the primary concerns, the rights of riparians were not ignored. Following the list of industry and government officials who gave testimony during the hearings, Mr. Magrath speaking for the IJC said:

> “These interests may be divided into two great groups, navigation interests and riparian interests. To these must be added the power interests responsible for the applications. The broad problem before the commission is to render a decision that will do substantial justice to all three.” (IJC 1914).

Government officials who spoke on behalf of the riparian and municipal interests during the hearings were primarily concerned with the effects regulation would have on the peak level of the lake during high supplies. The extreme level of 604.1 ft, 1903 datum, (184 meters, IGLD 85) experienced in 1869, was recent enough to be remembered. They were assured by U.S. Army Corps of Engineers Lieutenant Colonel Mason Patrick that 604.1 feet (184 meters) was still the expected maximum level of the lake, but that the average level of the lake would be higher as a result of regulating for power and navigation:

> “It is believed that if these compensating and regulating works be in place and properly operated, the mean elevation of Lake Superior will probably in the future be slightly above [602.27 ft, 1903 datum . . . the average for 1860-1913] (183.45 meters, IGLD 85); it may be as much above that as 0.4 or 0.5 of a foot (0.12-0.15 meters)” (IJC 1914).

Both the Corps of Engineers and the Canadian government stated (IJC 1914) that navigation would be seriously disrupted below Lake Superior levels of 602.1 ft (1903 datum at Marquette –183.4 m, IGLD 85). The Corps originally suggested regulation limits of 183.86 m and 183.1 m (603.6 ft and 601.1 ft, IGLD 55), but since that lower threshold caused problems for navigation, it was raised to 183.4 m (602.1 ft, IGLD 55). Since engineers stated that regulating the lake within less than a 2.5-foot (.76 m) range would be impractical, the final regulation range of 1.5 feet (.46 meters; 183.4 – 183.86) was set with the understanding that lake levels would vary 0.5 feet (.15 m) about those limits. The IJC intended those numbers to be a goal rather than an absolute limit. Their purpose was to prevent power and navigation interests from keeping the lake too high at the expense of riparians; it was understood that during times of high water supplies the high threshold would be exceeded. Figure 2 shows that the regulation goal was to keep Lake Superior on the high side of its normal range.

The 1914 Order of Approval was adjusted in 1979 when the IJC issued its Supplementary Order of Approval (IJC 1979) with regard to the regulation of Lake Superior. A study based on recorded levels from 1900 to 1967 conducted by the IJC to investigate further regulation of the Great Lakes basin concluded in 1976 (IJC 1976). The main impetus for the study was the record high levels set on Lakes Michigan-Huron during 1972 and 1973. Michigan-Huron riparians feared that the regulation of the Superior basin was being accomplished at their expense. Among other things, the report concluded that the basin would benefit from “systemic” regulation of Lake Superior; i.e., regulation of Lake Superior that takes into account the levels of downstream lakes. The new guiding principle was to maintain the levels of Superior and Michigan-Huron at the same relative positions within their recorded ranges, while not increasing the likelihood of Lake Superior exceeding 183.86 meters (602 feet, IGLD 55). The Supplementary Order also stated that “Lake Superior cannot be regulated within a one and one-half foot range . . . The regulated monthly mean level of Lake Superior shall not exceed elevation 602.0 IGLD (1955) or fall below elevation 598.4 IGLD (1955).” With that, the 1.5-foot regulation goal set forth in 1914 was officially replaced by a 3.6-foot (1.1 m) range.

As Hartmann (1988) pointed out, the evolution of the levels specified in the 1914 Order to those in the 1979 Supplementary Order is somewhat unclear, but it seems to be based on the original 1914 Order limits, translated to IGLD 55 using an average of several gages. The 1979 Supplementary Order reflects the intent of the original 1914 Order by specifiying a range of target levels for normal supply conditions.

> "The level of Lake Superior shall be maintained within its recorded range of stage when tested with supplies of the past as adjusted. The regulated monthly mean level of Lake Superior *shall not exceed* elevation 602.0 IGLD (1955) or *fall below* elevation 598.4 IGLD (1955) under these conditions." (ILSBC 1989).

"As adjusted" refers to the supplies for the period 1900 to 1976 and assumes an average flow for the diversions. The 598.4 to 602 range (feet, IGLD 55) translates to 182.76 to 183.86 meters, IGLD 85. These are the operating guidelines still in use at present. However, the true regulation objective is 183.4 to 183.86 meters because of Criterion C, one of the regulating principles established in the 1914 Order of Approval and reiterated in 1979. This criterion was designed to protect the levels of Lake Superior from falling too low under dry conditions:

> "To guard against unduly low levels in Lake Superior, the outflow from Lake Superior shall be reduced whenever, in the opinion of the Board, such reductions are necessary in order to prevent unduly low stages of water in Lake Superior, and shall fix the amounts of such reductions; provided that whenever the monthly mean level of the Lake is less than 600.5 IGLD (1955), the total discharge permitted shall be no greater than that which it would have been at the prevailing stage and under the discharge conditions which obtained prior to 1887." (IJC 1979).

Criterion C specifies that whenever the monthly mean level of Lake Superior falls below 183.4 meters (600.5, IGLD 1955), the total outflow shall be no greater than what would have occurred prior to 1887 with the same Lake Superior water level.

Chronology of Regulation Plans

The first regulation plan approved by the Board in 1921 was Sabin's Rule. Mr. L. C. Sabin, Senior Engineer at the Sault Ste. Marie, Michigan office of the U.S. Army Corps of Engineers, developed a rule for operating the compensating works that was used from 1921 until March, 1941. Sabin's Rule regulated flows between 1,444 and 3,568 m^3/s (51,000 and 126,000 cfs), ensuring 1,359 m^3/s (48,000 cfs) for power. The rule's objective was to keep Lake Superior's level as high as possible within the IJC directive of regulating the lake between 183.4 and 183.86 meters. Sabin's Rule was used more as a guideline than a rule; it was often ignored to appease power interests (Moore 1938). During the dry mid-1920s, the level of Lake Superior was drawn down more than 30 centimeters lower than the rule would have allowed (Moore 1938). In nearly half of the 72 months between 1921 and 1926, the mean level of Lake Superior fell below the IJC's absolute minimum level of 183.25 m. (International Lake Superior Board of Control 1934). The record for the lowest average Lake Superior level, 182.69 meters, was set in April, 1926.

During part of the 1920s and most of the 1930s, the levels of Lakes Michigan and Huron were much lower (compared to long-term means) than the levels of Lake Superior. This was despite the fact that Lake Superior was 15 to 30 cm lower than it would have been had Sabin's Rule been strictly applied. Residents of the Michigan-Huron basin were concerned about water being stored on Lake Superior (Fig. 3). In 1934, work began on developing a new rule for regulating Lake Superior. The rule that was developed was based on a lower minimum outflow for long periods. Power companies objected, and the rule was never put into use. In 1941, the U.S. Lake Survey was asked by the Lake Superior Board of Control to design a new rule to give maximum water for power without hurting navigation interests. The U.S. was considering building a new hydropower plant on the St. Marys River at the time. A series of rule curves were developed; P-1 through P-6 ("P" to denote power). After some analysis and testing, P-5 was chosen as the best compromise between power and navigation needs. This rule held the lake between 182.70 and 183.80 meters (600.0 and 603.6 feet, 1935 datum) based on the Marquette gage, providing more head for power than previous rules. Calculations showed that actual flows could be less than the specified minimum flows of 1,529 m^3/s (54,000 cfs) during winter and 1,614 m^3s (57,000 cfs) the rest of the year, about 4% of the time (Moore 1941). It took several years for the Canadians to consent to a test of P-5, but after it was in use, it was followed fairly closely until 1951.

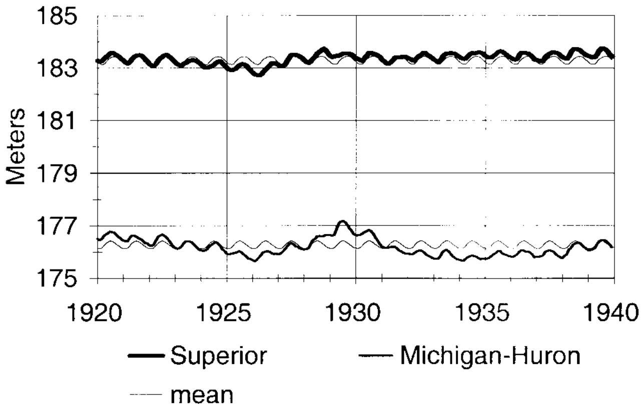

FIG. 3. Hydrographs of Lakes Superior and Michigan-Huron for the period 1920 to 1940 comparing recorded levels with the1860 to 1940 mean annual cycle. Concerns of Michigan-Huron basin residents that water was being stored on Lake Superior prompted development of a new regulation plan that went into effect in 1941.

During this same period, the Long Lac and Ogoki diversions from the Hudson Bay watershed into Lake Superior were initiated. The need for driving logs to Lake Superior brought about the Long Lac diversion project in 1939. In 1940, work began on the Ogoki Diversion in response to a great need for increased power production related to World War II. The diversion from the south end of Lake Nipigon was opened in 1943. Since that time, the average combined diversion into Lake Superior has been 160 m^3/s. Both Canada and the U.S. have benefited from the increased power production made possible by these diversions. However, the diversions made Rule P-5 obsolete. The Rule of 1949 was based on the principles of P-5, modified for the additional supplies. The objective was to pass the diversions through to Lakes Michigan-Huron without an increase in the level of Lake Superior; increasing the St. Marys outflows for the same Lake Superior stage. Since the Long Lac diversion had started in 1939 and the Ogoki in 1943, during the time P-5 was in use, the increased supplies had the effect of raising the level of Lake Superior.

The Rule of 1949, which went into effect in 1951, resulted in a gradual drop in the level of the lake of about 7.5 centimeters when the lake was above low water datum (Moore 1949). The Rule of 1949 was designed to pass the extra supplies out of Lake Superior, eventually returning the lake's level to what it had been prior to the diversions. Maximum St. Marys outflow under the Rule of 1949 was 3,511 m^3/s (124,00 cfs) during the navigation season and 2,407 m^3s (85,000 cfs) in winter. Minimum outflows were slightly higher than the minimum values under P-5, 1,642 and 1,557 m^3/s. This new rule was based for the first time on the lake level at the lake's outlet at Point Iroquois. The 1914 Order of Approval mandated that four gages be used to determine the average lake level, but at that time the effects of crustal movement on different gage readings was not realized. Since each of the four gages was on a different datum, the level at Marquette (1935 Datum) was used for P-5 and previous rules (Moore 1949). Starting with the Rule of 1949, the gage readings at Marquette, Duluth, Port Arthur, and Michipicoten were all translated to Point Iroquois values by adjusting for crustal movement. This was a significant improvement over past practices.

In September of 1955, the Rule of 1949 was modified by a redistribution of plan outflows. During periods of "normal" water supplies, water was stored on Lake Superior, which permitted greater outflows at other times, providing more hydropower production than the original rule. This use of storage was an improvement for hydropower interests by allowing outflows greater than the power requirements where the original Rule of 1949 would have called for minimum outflows. The 1955 Modified Rule of 1949 used the same minimum flow limits, but increased the maximum flow from 3,511 to 3,681 m^3/s (124,000 to 130,000 cfs). A one-half gate setting was added to the rule curve to protect fish, and allow flow through the navigation locks. The previous minimum gate setting had been zero. Minimum flows were 55,000 cfs in winter and 58,000 during the navigation season, as before. The main difference in effect between the Rule of 1949 and the 1955 Modified Rule of 1949, according to the test on the years after 1900, was a Lake Superior minimum stage about 1" higher than had been the case under the Rule of 1949 (Moore 1949). The modified rule was in use until September, 1973.

Extremely low lake levels on the Great Lakes during 1963 and 1964 caused widespread problems with drinking water quality and quantity, sanitation, transportation, and power concerns resulting in the governments of the U.S. and Canada requesting that the IJC oversee a study on further regulation of Great Lakes levels. Lakes Michigan-Huron experienced their lowest levels of record in 1964 and 1965. Shortly after the study began in 1964, the lake levels returned to average levels. Less than 10 years later, extremely high levels were experienced on the lakes (Fig. 4). The Lake Superior Board of Control was asked to modify Lake Superior regulation to provide some relief for the lower lakes from the high levels. Plan SO-901 was the first attempt to balance the levels of Lakes Superior and Michigan-Huron such that neither lake is in a more favorable position with respect to its long-term mean. This new rule was used as a guide for regulation during the mid-1970s. It was the first regulation plan that considered the effects of regulating Lake Superior on the lower lakes. This plan maintains the same minimum outflows as the 1955 Modified Rule of 1949 during the winter. Plan SO-901 calls for a lower minimum outflow during the navigation season (55,000 cfs rather than 58,000). The plan was in use through September, 1979.

Record-setting low levels were experienced on Lakes Michigan and Huron during the 1960s. Little more than 10 years later, record high levels were endured. Many riparians that had built along the wide beaches of the 1960s suffered flooding and worse during the 1970s. The Levels Reference Study that began in 1964 concluded with a report (IJC 1976) which rejected four and five-lake regulation as a solution to the recent problems, but did recommend improving the Lake Superior regulation plan by reexamining the 1914 Order of Approval. (IJC 1976) The IJC issued formal amendments to the 1914 Order of Approval on 27 September 1978 and 3 October 1979. These came to be known as the Supplementary Orders of Approval. The Supplementary Orders called for regulating the outflows of Lake Superior in a systemic way, considering the impacts of Lake Superior regulation on the downstream lakes.

In October 1979, Plan 1977, developed by the International Lake Superior Board of Control, was adopted as the new regulation plan for Lake Superior, replacing Plan SO-901. Plan 1977 employed monthly water supply forecasts to minimize gate changes and keep the St. Marys flows as uniform as possible. Using monthly forecasts was also intended to decrease the frequency of both extreme high and extreme low levels on Lakes Superior, Michigan-Huron, and Erie. Plan 1977, like SO-901, is based on balancing the levels of Superior and Michigan-Huron with respect to their long-term means, while striving to keep the average level of Lake Superior between 600.5 and 602.0 feet, IGLD 1955 (183.4 and 183.86 meters, IGLD 85). A long list of criteria concerning both levels and flows of

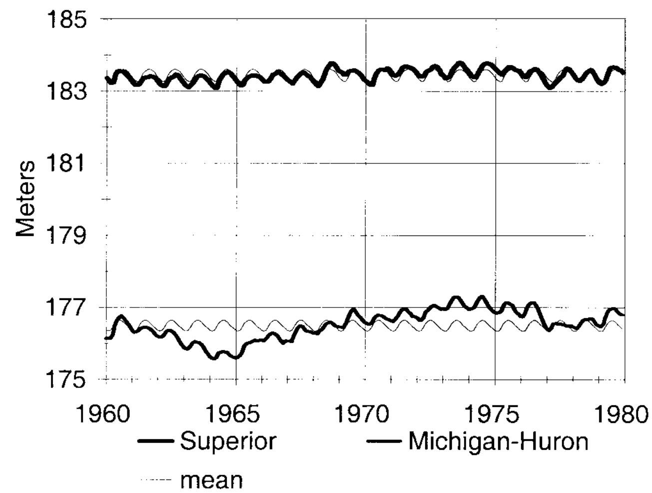

FIG. 4. Hydrographs of Lakes Superior and Michigan-Huron for the period 1960 to 1980 comparing recorded levels with the 1860 to 1980 mean annual cycle. The difficulties experienced by residents of the Michigan-Huron basin prompted a new regulation plan in 1973 that took downstream lakes into consideration for the first time.

Lakes Superior and Michigan-Huron are based on complying with the Orders of Approval, 1914 and 1979.

Several significant physical changes affecting the St. Marys flows eventually made alterations to the regulation plan necessary. The Canadian power authority redesigned their Sault Ste. Marie hydropower plant, effectively increasing the flow capacity of the river. In addition, the Fishery Remedial Works, authorized by the IJC after an extensive study by all relevant interests, were completed, protecting both flow in the rapids and the sport fishery. The International Lake Superior Board of Control implemented Plan 1977-A on a trial basis in June 1990. Plan 1977-A is based on the same guiding principles as Plan 1977: to manage Lake Superior outflows so that the levels of Lakes Superior and Michigan-Huron are at the same position relative to their long-term means. The new plan made modifications to increase the efficiency of the regulation process based on changes in the physical system and 10 years of experience running Plan 1977. Improvements of Plan 1977-A over Plan 1977 included: smoother transition from fall to winter flows by using a moving 5-month forecast; better provisions to guard against flooding below the locks; better balancing between Superior and Michigan-Huron during low levels; allowing flows between 55,000 and 65,000 cfs. When tested over the period 1900 to 1986, Plan 1977-A reduced the range of fluctuations of Lake Superior levels, reduced the frequency of low levels, and was a smoother plan operationally than Plan 1977. It also reduced the number of gate changes necessary and took advantage of the increased hydraulic efficiency of the St. Marys River. Plan 1977-A is still the regulation plan in use today.

Criterion C, the stipulation in the Orders of Approval that pre-project flows be used in place of plan flows when the monthly mean level drops below 183.4, was accidentally omitted from the original computer program of Plan 1977-A used by both the U.S. Army Corps of Engineers and Environment Canada. Operationally, for several years this flow limitation was applied by manual check after the results of the Plan 1977-A program were obtained. This may have caused some deviations from what the 1914 Order of Approval intended (Lee 1992), particularly when the mean level of Lake Michigan-Huron was lower with respect to its mean than was Lake Superior. Without Criterion C under these conditions, the level of Lake Superior would be drawn down by more than the Orders had intended. At this point, Criterion C is fully integrated in the regulation plans in use by both countries.

ANALYSIS OF REGULATION IMPACTS

In order to evaluate the role of regulation in controlling the levels and flows of the upper Great Lakes, the 1887 stage-discharge relationship was used to develop a simulation of pre-regulation conditions to be used as a baseline for comparison. For the natural outlet conditions, the St. Marys River flows are described (Quinn 1978, Southam and Larson 1990) by the rating equation:

$$Q_{sm} = 824.7 * (Z_i - 181.43)^{1.5} - ice \qquad (1)$$

where: Q_{sm} = St. Marys River flow in m^3/s
Z_i = Lake Superior level at Pt. Iroquois in m, IGLD 85
ice = St. Marys River winter ice retardation in m^3/s.

This equation was used to develop a set of pre-regulation levels and flows against which to evaluate what has actually occurred given the channel modifications and regulation schemes that have dictated the St. Marys outflows for 80 of the last 100 years. The new Coordinated Great Lakes Regulation and Routing Model (CGLRRM), developed by the NOAA Great Lakes Environmental Research Laboratory, the U.S. Army Corps of Engineers, and Environment Canada, was used to produce these simulated natural levels and flows. Basis of Comparison (IJC 1993) net basin supplies for 1900 to 1999 and actual diversions and ice-weed retardation values were used to run the model. The model produces lakewide average monthly levels, so the results are compared with the Corps' lakewide average recorded levels, which begin in 1918.

In the very early years of regulation, Lake Superior experienced its record low level of 182.69 meters in 1926. Without regulation, the model indicates that level could have been 8 to 10 cm lower. More significantly, however, the regulation of Lake Superior during this dry period kept the average level of the lake above 183 meters except for about 18 months. Without the controls at the head of the St. Marys River, the average lake level would have fallen below 183 for 3.5 years, and the St. Marys River flow would remain below the regulation minimum limit of 55,000 cfs (1,557 m^3/s) for most of that period, also.

Regulation protected Lake Superior levels from falling too low during the dry period of 1931 to 1934, keeping the average level of Lake Superior more than 30 cm higher than it would have been under pre-regulation conditions for more than 3 of the driest years. Model runs show that the lake level would have dropped below 183 meters during the winter months of 4 consecutive years if the lake's outlet had not been controlled. Figure 5 summarizes the differences between recorded Lake Superior levels and "preregulation" levels according to the simulation model for the period 1917 to 2000. It is readily apparent that regulation has kept the lake higher than "natural" for most of this century.

Lakes Michigan and Huron were also spared much lower levels during this time period. Comparisons between recorded average levels and simulated pre-regulation levels show a 20 to 25 cm effect. Without regulation during this dry period, minimum records (below 175.58 m, IGLD 85) would have been set on Lakes Michigan and Huron for 11 months during the 1933 to 1937 period, according to this simulated comparison.

Another low period was experienced in the 1960s. This was felt most drastically on Lakes Michigan and Huron, as basin residents experienced their all-time low of 175.58 m during the spring of 1964. Comparisons with the pre-regula-

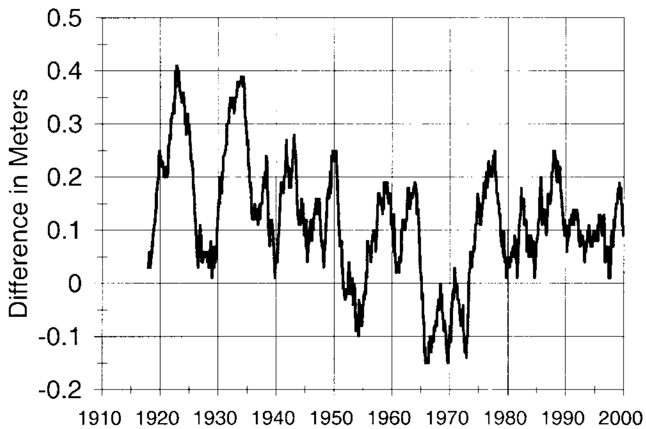

FIG. 5. The difference between recorded and simulated "pre-regulation" levels for Lake Superior. Positive values indicate that regulated levels on Lake Superior are higher than they would have been under "natural" conditions, often by 15 to 20 cm.

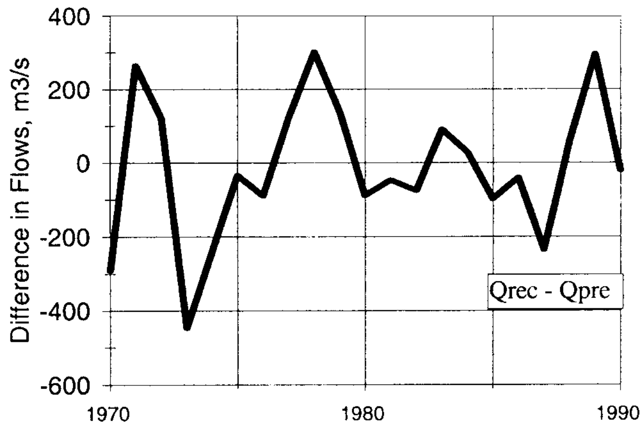

FIG. 6. The difference in outflows (recorded minus pre-regulation) between recorded and simulated "pre-regulation" levels for Lake Superior from 1970 to 1990. Positive values indicate that more water is being released from the lake than the "natural" condition. The negative values in the 1970s and 1980s show that water was being held on Lake Superior during these periods of high supplies.

tion model run reveal that regulation did very little during this period to protect the levels of Michigan-Huron from the extreme lows. The pre-regulation level would have been from 2 to 5 cm lower. The regulation of Lake Superior before 1973 ignored the levels of downstream lakes. The levels of Superior in 1963 and 1964 were low, but not critically low.

The 1970s and 1980s provided an opportunity to observe the effects of regulation on extremely high levels. Lake Superior set record highs in 1974 and 1975 and again in 1985 and 1986. The pre-regulation model comparison suggests that Lake Superior was kept artificially high during the mid- to late 1970s. Unregulated levels would have been on average 15 to 20 cm lower than the recorded monthly average lakewide levels for Lake Superior. Lakes Michigan-Huron and Erie were kept somewhat lower by regulation during this period. Comparisons with the pre-regulation model run show that regulated levels were 5 to 10 cm lower than they would have been in an unregulated state. This happened just after the regulation changed to Plan SO-901, which mandated balancing Superior and Michigan-Huron. Extremely high water supplies strained the regulation limits of Plan 1977. Record high levels were set on Lakes Superior, Michigan-Huron, and Erie during 1985 and 1986. Comparisons show that the recorded level of Lake Superior was 15 to 20 cm higher than the simulation of the pre-regulation level. One year later, a lack of winter precipitation caused a rapid decline in lake levels. Comparison with the pre-regulation model indicates that Lake Superior was kept higher by regulation during the lowest period by about 20 cm. Figure 6 shows the differences between recorded and "pre-regulation" Lake Superior outflows between 1970 and 1990. For most of this period, the regulation plan in effect was attempting to balance storage between Lakes Superior and Michigan-Huron. However, it is apparent that during the high supplies of the 1970s and mid-1980s, water was held on Lake Superior.

A second way to evaluate the impacts of regulation on the levels of Lake Superior is to compare the frequency distributions from different time periods. The three different time periods shown are: Figure 7a) 1921 to 1999, the entire period of regulation; 7b) 1921 to 1972, the period when regulation was based on Lake Superior levels and flows only; and, 7c) 1973 to 1999, the years when regulation was based on balancing the levels of Superior and Michigan-Huron. The most notable feature of these comparisons is the difference between the two regulation schemes. During the period when the regulation of Lake Superior was based entirely on its own level (Fig. 7b), the occurrence of high levels on Lake Superior has slightly decreased (from 20% to 13%). This decrease is due to two time periods: 1951 to 1955, and 1965 to 1972. However, the com-

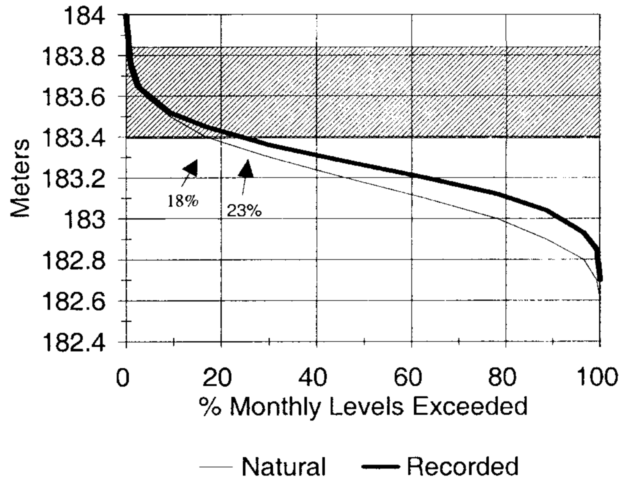

FIG. 7A. Frequency distribution for 1921 to 1999, the entire period of regulation. Regulation of Lake Superior has increased the occurrence of high lake levels by 5%.

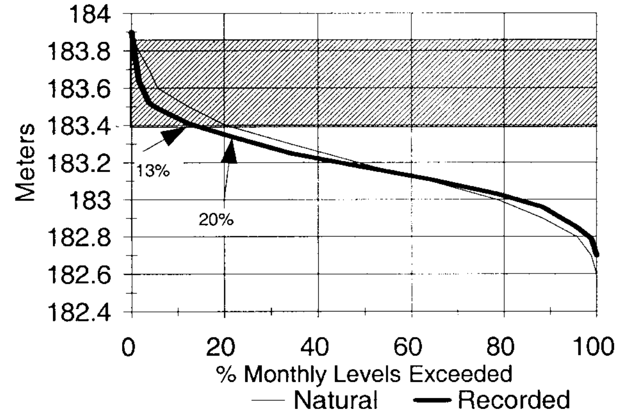

FIG. 7B. Frequency distribution for 1921 to 1972; regulation based on Superior only. When regulation was based on Superior levels only, high levels were reduced by 7%.

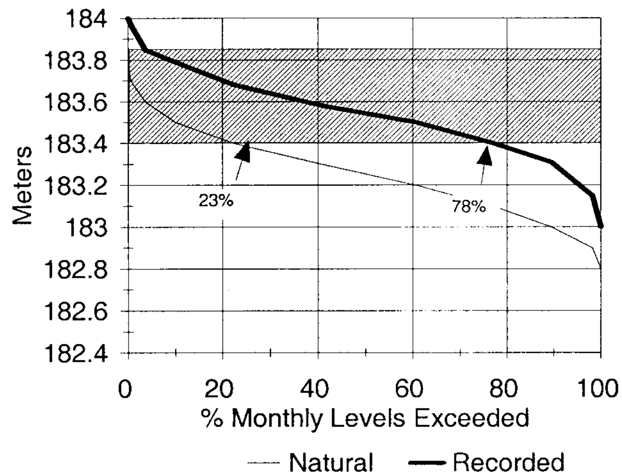

FIG. 7C. Frequency distribution for 1973 to 1999, regulation based on balancing. During recent years when regulation of Lake Superior was based on balancing storage between Superior and Michigan-Huron, regulation more than tripled the occurrence of high levels on Lake Superior. This period also included some very high supplies.

parison of frequency distributions for 1973 to 1999 (Fig. 7c) shows regulation more than tripling the occurrence of levels in the regulation range (from 23% to 78%), a result of having to consider the level of Lakes Michigan and Huron. It is also important to note that unusually high supplies were experienced during this nearly 30-year period.

The Current Regulation Plan: 1977-A

The final approach to evaluating the potential impacts of controlling the levels and flows of the upper Great Lakes, particularly the current regulation plan, is to simulate Plan 1977-A levels over the past 100 years. This simulation was run using the new CGLRRM with actual net basin supplies and diversions along with average ice/weed retardation values for the connecting channels. The results of this simulation tell us what, theoretically, would have happened if Plan 1977-A had been in effect for the last 100 years, given the same supply conditions and diversions.

The most striking difference between the recorded Lake Superior levels and the simulated levels that would have been experienced under Plan 1977-A occurs during the 1930s and early 1940s. The level of Lake Superior was from 15 to 20 cm higher under the early regulation plans than would have been the case under Plan 1977-A (Fig. 8). The same disparity is observed between the recorded and modeled levels of Lakes Michigan and Huron during this time period.

Long Lac-Ogoki Diversion

Between 1939 when the diversions went into effect and 1960, three different regulation plans and a wide variety of water supply conditions dominated

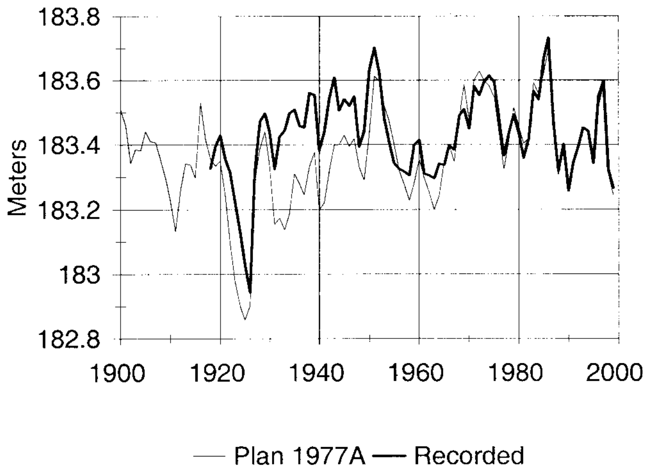

FIG. 8. Plan 1977-A versus recorded Lake Superior levels (annual averages).

the changing levels and flows of Lake Superior. From 1941 to 1951, P-5 was the Lake Superior regulation plan. Regulated levels were 10 to 20 cm higher during this period than unregulated levels. Part of the lake level increase during this time could be attributed to the new supplies that were not accounted for by the regulation plan. Thus, in 1951, the Rule of 1949 went into effect. The primary reason for the new rule was to pass the Long Lac-Ogoki diversion downstream without impacting the level of Lake Superior. In 1949 when the new rule was being developed, the average monthly diversion was 113 m^3/s (4,000 cfs). Although the clear intent was to pass on that entire amount, Sherman Moore's account of developing the new rule curve states:

> "[increasing the minimum flow by 4,000 cfs] was impossible, the line for maximum and that for minimum flows crossing each other. An increase of 1,000 cfs was made, which left a reasonable space between the two lines." (Moore 1949).

The 28 m^3/s (1,000 cfs) that was passed through Lake Superior was a very small portion of the approximately 145 to 160 m^3/s diversion into the basin. It is unclear whether or not that amount was ever increased in subsequent regulation plans. The Rule of 1949 appears to have done an excellent job of mirroring unregulated levels from 1951 to 1955. When the Modified Rule of 1949 went into effect in 1955, recorded levels went back to 10 to 15 cm above unregulated. The purpose of the modification was to conserve water during non-critical periods, increase maximum outflows, and to increase the water available for power interests.

When analyzing the impacts of a diversion on a regulated lake such as Superior, it is imperative that the manner in which the regulation plan accounts for the diversion be explicitly stated. Starting in 1951, the Long Lac-Ogoki diversions have had no effect on the levels of Lake Superior because the Rule of 1949, and all subsequent regulation plans, passed the extra supply downstream. They have raised the level of downstream (unregulated) lakes, however. When the rule of 1949 went into effect in 1951, the level of Lake Superior dropped 7.5 cm according to Sherman Moore, Corps engineer (Moore 1949), presumably to the level it had been prior to 1939. It is not hard to find references that state that Lake Superior would be 6 cm higher without the Long Lac-Ogoki diversion (International Great Lakes Diversions and Consumptive Uses Board 1981, IJC 1999). This misleading statement means that if the diversion were curtailed and the *present* regulation were continued, the level of Lake Superior would drop by 6 cm. In fact, though, if this diversion were altered, the change would be accounted for by changes to the regulation plan. The difference between the "unregulated" level of Lake Superior and the "unregulated" level with no Long Lac-Ogoki according to model simulations is between 1 and 10 cm, but 6 to 7 appears to be a good average. If the average rate of these diversions has increased since 1951, this has contributed to an increase in the level of Lake Superior unless those supplies were also accounted for each time the regulation plan changed.

THE FUTURE

The traditional approach to evaluating changes needed by Lake Superior's regulation plan has been to examine historical levels and past practices to seek potential improvements. What is called for now is a broader view. Climate change must be considered. Stochastic analysis of historical net basin supplies can also be used to provide a more rigorous set of extreme conditions that can be instructive in testing new plans.

The effects of global warming on Great Lakes levels and flows was recently investigated as part of the National Assessment of Climate Change (Lofgren *et al.* 2002, Sousounis and Bisanz 2000). Two general circulation models were used to evaluate the effects of doubling CO_2 in the atmosphere on the water resources of the Great Lakes region. Both the HadCM2 (Hadley Centre—Great Britain) and CGCM1 (Canadian Climate Centre) models predicted higher lake surface water temperatures and correspondingly higher lake evaporation. The models differed in whether they saw precipitation increasing or decreasing, but for the Superior basin, both models predicted an increase. The CGCM1 model predicted higher air temperatures, slightly higher precipitation, and greatly increased evaporation, yielding dramatically lower lake levels in as little as 30 years. The HadCM2 model results were less extreme, predicting just slightly warmer and wetter conditions leading to small lake level increases (Lofgren *et al.* 2002).

The general circulation models (gcms) were run with continuously changing greenhouse gas forcing over the period 1900 to 2100. The analysis used a base period of 1961 to 1990, and future 20-year segments centered about 2030, 2050, and 2090. The 2050 run most closely approximates doubled atmospheric CO_2 concentration relative to the base period. The results from the gcms were used to run Croley's hydrologic modeling suite (1983), calculating heat budgets for each of the lakes using daily means of meteorological forcing factors. The runoff model, also part of the modeling suite, then calculated net basin supplies that are used to generate predicted lake levels and flows by way of the Coordinated Great Lakes Regulation and Routing Model.

Using the CGCM1 model results as a "worst case" scenario for looking at future water supply issues, the Base (1954 to 1995) and 2050 monthly mean lake levels are superimposed for Lake Superior (Fig. 9). The predicted lake levels from Base to 2030 and from Base to 2050 drop an average of 22 and 31 cm, respectively. The current regulation plan would call for "pre-regulation" outflows (Criterion C conditions) almost continuously. The corresponding declines for Michigan-Huron are an average 72 cm from Base to 2030 and approximately 1 m from Base to 2050. It is noteworthy that according to the CGCM1 model, the potential lake level changes are much more dramatic on Lakes Michigan-Huron than on Superior, which could result in a shift in the balance between the two lakes that would need to be taken into consideration in the regulation scheme. Results for the Hadley Centre model are much less dramatic. For Lake Superior, the predicted difference between Base and 2050 was an average decline of 1 cm. Lake Michigan-Huron ex-

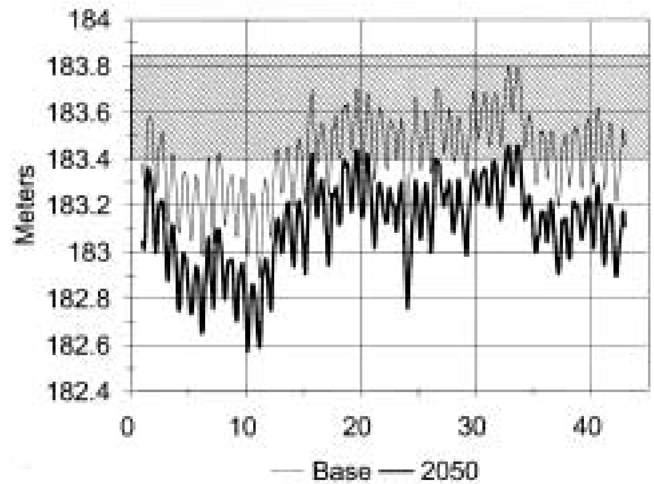

FIG. 9. Lake Superior levels based on Canadian Climate Centre model, CGCM1. The comparison of Base (1961 to 1990) with 2050 (2030 to 2071) indicates a drop in lake levels of approximately 0.3 meters due to greatly increased evaporation caused by warmer air temperatures.

perienced an average increase in level from Base to 2050 of 3 cm.

The policy and management implications of a 20 cm drop in Lake Superior or a 72 cm drop in Lakes Michigan-Huron are huge. The Lake Superior regulation plan would have to be reevaluated. The Chicago Diversion would be in danger if Lakes Michigan-Huron dropped more than 0.5 m, posing serious health risks to the Chicago area, since the diversion serves to move wastewater away from the city's source of drinking water. The only alternative would be expensive dredging of the canal (Mortsch *et al.* 1998). The shipping and hydropower industries would be severely hampered by drops of this magnitude.

Since any evaluation of future water supplies should include both highs and lows, a 50,000-year set of stochastic net basin supplies developed during a previous study was used to provide hypothetical upper and lower bounds to future water supplies in the Great Lakes (Lee *et al.* 1994). The study to determine spillway adequacy upstream of Montreal was commissioned in the early 1990s by a Canadian power company, Hydro-Quebec, and was conducted in conjunction with scientists from the NOAA Great Lakes Environmental Research Laboratory. To ensure that the tests were sufficiently representative of extreme high and low supplies, a set of simulated net basin supplies was developed based on current climate, statistically rearranged. These stochastic supplies were used to run the current regulation and routing models to produce simulated levels and flows. The operational programs for both Plan 1977-A (Lake Superior) and Plan 1958D (Lake Ontario) had to be altered to make them run under the extreme low and high conditions produced by the stochastic net basin supplies.

For the purposes of this study, three 60-year periods were selected from the 50,000 years of stochastic net basin supplies: 1) the period containing the highest supplies; 2) the period containing the lowest supplies, and; 3) the period containing the most variable (high and low) supplies. These three sets of net basin supplies were used to generate levels and flows by way of the CGLRRM. They might serve as reasonable upper and lower bounds for evaluating future regulation strategies in the Great Lakes. Figure 10 shows the results of the high and low scenarios plotted against each other. Both sets of extreme supplies cause Plan77-A to fail. The high NBS scenario violates the current regulation plan's "maximum" goal of 183.86 m three times during the 60 years, but both the high and low scenarios fall below the low threshold of 183.4 m quite often. The low NBS scenario resulted in levels below 182.76 m, the absolute minimum threshold specified by the Orders of Approval, for approximately 12 months during a 3-year period.

The 60-year period containing both highs and lows caused the CGLRRM to fail. This was somewhat significant because the new routing model was designed to withstand extreme conditions. The model crash seems to be related to levels changing too quickly on Lake St. Clair caused by the rapidly changing net basin supplies of this scenario.

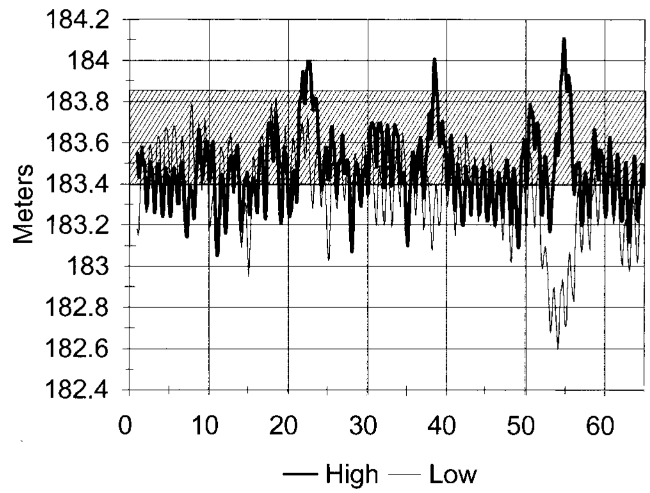

FIG. 10. Lake Superior levels produced by stochastically-generated series of net basin supplies. The experimental net basin supplies were developed based on present climate to provide extreme highs and lows for testing future models. This shows the levels produced by the segment with the highest supplies and the one with the lowest supplies.

CONCLUSIONS

Regulation has altered the levels and flows of Lakes Superior and the lower lakes for the past 80 years. The principles guiding the regulation of Lake Superior were established in 1909 and 1914. Even though those Orders of Approval were revisited and somewhat refined in 1979, the management strategy has not deviated from the early 1900s, when the control of Lake Superior's outlet was clearly for the purpose of maintaining high levels on the lake for navigation and hydropower. Unlike the regulation plan for Lake Ontario, protection of riparians is not as important a guiding principle as are other concerns in the existing Superior regulation plan. When the International Lake Superior Board of Control mandated in 1979 that systemic regulation would be a more reasonable approach, riparians in the Michigan-Huron basin may have benefited more than those who own property along the shores of Lake Superior. In 1985 and 1986, extremely high supplies were experienced in the Great Lakes basin. Record highs were experienced on all of the upper lakes, but not on Lake Ontario. This may have been because Lake Ontario is regulated to prevent extremely high levels. Differences in water supplies to the upper and lower lakes could also be responsible.

Comparison of recorded monthly average levels with the pre-regulation modeled "natural" levels allows conclusions to be drawn on how regulation has impacted record levels on Lake Superior and the lower lakes. During the extreme low period in the 1920s, the natural level would have been 8 to 10 cm lower than the 182.69 m record low (Fig. 11). However, record highs would not have been experienced in 1985 on Lake Superior according to this comparison. The peak would have occurred between 10 and 20 cm lower than the 183.91 m (monthly average) record. The low records that were set on Lakes Michigan-Huron in the 1960s would have been even lower in the absence of regulation by 5 to 10 cm. The regulation of Lake Superior has prevented some very low levels from

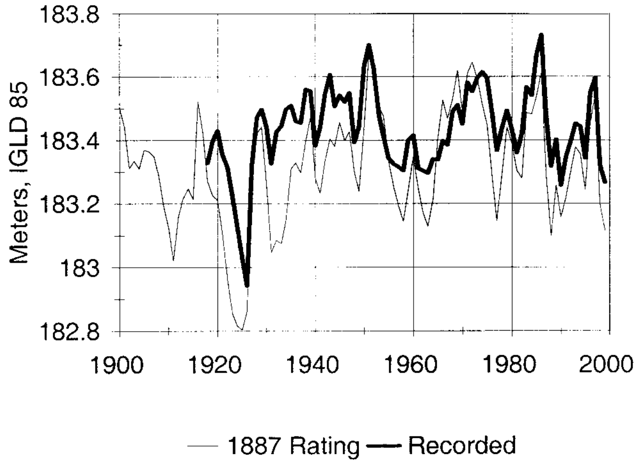

FIG. 11. Comparison of recorded levels with "natural" (1887 Rating) levels for Lake Superior. Regulation appears to have prevented (by at least 10 cm) even lower levels in the 1920s and 1960s. This also shows that regulation increased the peak high levels in the 1980s by over 10 cm.

falling even lower. It has also exacerbated the extremely high levels, causing record highs on Lakes Superior and Michigan-Huron to be 10 to 20 cm higher than the pre-regulation model indicates the natural level would have been.

The use of Lake Superior as a storage basin to prevent downstream flooding creates as many problems as it solves. In 1985, with Lakes Michigan-Huron and Erie at extremely high levels (40 to 50 cm above long-term averages) and Lake Superior just 14 cm above its long-term average, the IJC asked the International Lake Superior Board of Control to deviate from the plan and reduce Superior outflows to protect the downstream lakes. When unusually heavy August precipitation caused Lake Superior levels to increase rapidly, outflows were increased to try to keep levels below the mandated 183.86 m, IGLD 85. Despite those measures, record highs of 183.91 m were set in October and November on Lake Superior. A small measure of temporary relief was felt downstream, but both Lakes Michigan-Huron and Lake Erie set record highs despite the actions taken. As illustrated by Lee and Clites (1997), probabilistic forecasts could be useful to the Lake Superior Board and IJC in making policy decisions such as this.

The IJC has already begun the initial steps to reevaluate the regulation plan for Lake Superior. This is an excellent opportunity to revisit the reasons behind regulating the lake. The water management venue is quite different now than it was in 1914. Land use and the economy have changed. There may be interests and concerns that weren't explicitly considered in 1914 that should be considered now. When Plan77-A is replaced with a new model, it should be tested on as many sets of levels as possible, not just the recorded levels which reflect numerous changes in channel conditions and regulation schemes. Simulated unregulated levels should be used as well as climate change scenarios or other extremes, to ensure that the next regulation plan for Lake Superior is sufficiently rigorous to stand the test of time.

It is important to note that although Lake Superior is "regulated," this does not mean that the International Lake Superior Board of Control can fully control its levels. The compensating works allow modifications to lake levels and flows, but certainly not control in any absolute sense. Uncertainty is implicit with any management decision. There are numerical tools now available that could be used during times when deviations from the plan are warranted to increase the information about the situation and decrease the amount of uncertainty for managers. Probabilistic water supply forecasts could help the International Lake Superior Board of Control make more informed decisions and might also serve to remind those whose livelihood or property are impacted by changing lake levels that a regulated lake the size of Lake Superior is not really controlled.

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